NOLTR 61-108

CHARACTERIZATION OF SQUIB, MK 1 MOD 0: THERMAL STACKING FROM RADAR-LIKE PULSES

15 SEPTEMBER 1961

NOL

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

NOLTR 61-108

CHARACTERIZATION OF SQUIB, MK 1 MOD 0: Thermal Stacking from Radar-Like Pulses (U)

Prepared by:

L. D. Hampton & J. N. Ayres

Approved by: Anson D. Solem
Chief, Explosion Dynamics Division

ABSTRACT: The electro-thermal equations describing the heating and cooling of wire bridge electro-explosive devices are solved for constant-current radar-type input pulses. The bridgewire temperature-time history is obtained for a variety of pulse amplitudes and repetition frequencies. Equilibrium temperatures are obtained for the varied input conditions and are all combined in a single nomograph. If the hot-spot theory is assumed the conditions for explosion can be deduced. For instance, for the Mk 1 Squib, a temperature rise of 500°C will result if the value of I^2RW is 1,000 microjoules at a very low pulse repetition frequency (below 60 cps.) or is 100 microjoules at a frequency of 2,000 cps. This temperature rise would be expected to cause the squib to fire approximately 50% of the time.

PUBLISHED OCTOBER 1961

Explosions Research Department
U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

NOLTR 61-108 15 September 1961

The work described in this report was undertaken as part of the program on the Hazards of Electromagnetic Radiation to Ordnance (HERO). It describes theoretical calculations which attempt to show how the temperature of a wire bridge EED is elevated by repeated radar pulses.

The work should be of interest to those working on the HERO program, to those using electro-explosive devices in ordnance applications, and to those actively designing, developing, and testing electro-explosive devices.

W. D. COLEMAN
Captain, USN
Commander

C. J. Aronson

C. J. ARONSON
By direction

CONTENTS

ILLUSTRATIONS

REFERENCES

(1) L. A. Rosenthal, "Electro-Thermal Equations for Electro-Explosive Devices (U)", NavOrd Report 6684, 15 August 1959.

(2) F. P. Bowden and A. D. Yoffe, "Initiation and Growth of Explosion in Liquids and Solids", Cambridge at the University press, 1952.

(3) I. Kabik, L. A. Rosenthal, and A. D. Solem, "The Response of Electro-Explosive Devices to Transient Electrical Pulses", NOLTR 61-20, 17 April 1961, Unclassified.

CHARACTERIZATION OF SQUIB, MK 1 MOD O: Thermal Stacking from Radar-Like Pulses (U)

1. INTRODUCTION

1.1 The mechanism of initiation of wire bridge electro-explosive devices (EEDs) has been studied at this Laboratory in considerable detail. An electro-thermal model has been proposed (reference (1)) which states that the explosive is triggered when the wire bridge has been raised to a particular temperature by "I^2R", or ohmic, heating of the bridgewire. Experimental data obtained to date have not required an alteration of the basic premise.

1.2 These studies have been of particular interest to, and have been in large supported by, the HERO (Hazards of Electromagnetic Radiation to Ordnance) program. In assessing the vulnerability of an EED to specific electrical environments, it is desirable to be able to predict the probability of its response to various types of electrical inputs.

1.3 The present report deals with the computation of the temperature-time relationships of the bridgewire of an EED when it is subjected to a radar-like train of RF bursts or pulses. The general theory of the electro-thermal model, the digital computation methods, generalizations, and a nomogram of typical results will be given in this report.

1.4 The Squib, Mk 1 Mod O, has been studied in great detail by the Naval Ordnance Laboratory. It is considered to be typical or at least analogous to the wire bridge EEDs in general use in the explosives field. Thus, while the theory and detailed computations have been applied directly to this particular EED, it is firmly believed that the work herein can be applied directly, or with little change, to many other specific EEDs. It will therefore be left to the reader to make such adaptations or extensions as may be necessary to suit his individual needs rather than to give a broader and more comprehensive treatment to the subject.

2. THEORY

2.1 The Squib, Mk 1 Mod 0, (shown in Figure 1) has been considered as a lumped parameter system. The platinum-iridium bridgewire plus its immediate surroundings (explosive when loaded, air before loading, or explosive simulant when dummy loaded) has a heat capacity represented by C_p. It is assumed that C_p is independent of the bridgewire temperature.

2.2 The dissipation of electrical energy in the bridgewire causes the bridgewire to be elevated in temperature by an amount, θ. The bridgewire is known to be cooler at the ends than in the center because of the cooling of the support posts. For simplicity, the bridgewire temperature is considered to be an average of the temperature along its length. The hottest point on the wire will be the most likely to cause initiation. Yet, experimentally, this hottest point does not differ markedly from the average temperature.

2.3 A steady state condition of electrical energy dissipation in the bridgewire will lead to a corresponding steady state flow of thermal energy into the support posts and into the explosive, or simulant, in contact with the bridgewire. Under these steady state conditions the heat energy flow, and therefore the electrical energy input, will be proportional to the temperature elevation, θ. The proportionality constant, γ, is designated as the heat loss factor.

2.4 These parameters can be combined in an instantaneous energy-balance equation

$$C_p \frac{d\theta}{dt} + \gamma\theta = P(t),$$

where P(t) is the power time function.

From this differential equation θ (t) functions can be derived which describe the thermal response of the EED bridgewire to various electrical input wave-forms. Experimental verification of the equation is facilitated by the technique of using the EED bridgewire as its own resistance thermometer. The change of bridgewire resistance with temperature can be expressed (using again the idea of lumped constants and of θ as the average bridgewire temperature elevation) by

$$R = \mathring{R}(1 + \alpha\theta)$$

where $\mathring{R}$ is the resistance of the EED at a stated reference temperature.

and α is the corresponding temperature coefficient of resistance measured for a temperature change from this same stated reference temperature.

This relationship is based on the assumption that the resistance varies linearly with the temperature throughout the practical temperature range.

2.5 Because of the low resistance of the EED compared to the probable magnitudes of source impedances that might be expected in weapon circuitry carrying RF power, it was decided to consider the case for constant-current pulse trains. An additional reason for this choice is that, for EEDs with a positive value of the coefficient, α, heating of the bridgewire raises its resistance and therefore increases the power it absorbs, even though the pulse amplitude is unchanged.* Constant current pulse data would therefore provide a conservative basis for making system safety estimates. The differential equation expressing the lumped parameter behavior under constant current input conditions is:

$$C_p \frac{d\theta}{dt} + \gamma\theta = I^2\mathring{R}\,(1 + \alpha\theta) \qquad (1)$$

which can be solved to yield

$$\theta_W = \frac{I^2\mathring{R}}{\gamma - I^2\mathring{R}\alpha}\left[1 - \exp\left(\frac{I^2\mathring{R}\alpha - \gamma}{C_p}\cdot W\right)\right] \qquad (2)$$

where W is the pulse length

and θ_W is the temperature at the end of the pulse.

2.6 Whenever the bridgewire temperature is above ambient with no power applied, the differential equation expressing the bridgewire cooling will be found to apply:

$$C_p \frac{d\theta}{dt} + \gamma\theta = 0. \qquad (3)$$

*Positive values of α cause constant voltage pulses to deliver less power as the temperature rises, i.e.,

$$P = \frac{E^2}{\mathring{R}\,(1 + \alpha\theta)} = \frac{\mathring{P}}{1 + \alpha\theta}.$$

Taking time, t, measured from the instant the power is removed and cooling begins, and taking the bridgewire temperature to be θ_m at the instant $t = 0$, equation (3) can be solved:

$$\theta_c = \theta_m \exp\left[-\frac{\gamma t_c}{C_p}\right] = \theta_m \exp\left[-\frac{t_c}{\tau}\right] \qquad (4)$$

where τ, the thermal time constant, equals $\frac{C_p}{\gamma}$,

t_c is the cooling time between current pulses,

and θ_c is the temperature at the end of the cooling time.

2.7 To obtain the temperature-time history of an EED subjected to a train of constant current pulses it is necessary to apply equations (2) and (4) in alternation in as many cycles as may be appropriate to the study.

2.8 If the cooling portion of the cycle is long compared to τ, the bridgewire will return to ambient temperature at the end of the cycle. In this case each cycle will repeat the history of the preceding cycle. If the pulse repetition frequency, that is the frequency at which the pulses are repeated, is increased by decreasing the cooling portion of the cycle beyond a certain point, then at the beginning of the pulse train the loss of heat during cooling will be less than the gain during the heating portion of the cycle. In this case the temperature of the bridgewire will be greater for one cycle than it was for the preceding one. As a result of this increase in temperature both the rise and fall of temperature during the heating and cooling portions of the cycle are increased. However, since the increase in the rise of temperature during the heating portion of one cycle with respect to that of the preceding cycle is linear and the fall in temperature during the cooling portion increases exponentially, the loss of heat due to cooling will eventually become equal to the gain in heat during the heating portion and the temperature of the wire again goes through a stable history from one cycle to the next as shown in Figures 2 and 3. If the input energy in the constant current pulses is high enough then the bridgewire temperature will rise high enough to initiate the explosive surrounding it. If the energy is not high enough the bridge temperature will stabilize at a value lower than the ignition temperature of the surrounding explosive.

3. COMPUTATIONS AND RESULTS

3.1 An IBM 704 Computer was programmed to express the constant current heating with alternate natural cooling. The Fortran Program is given in Appendix A. The input data for the IBM 704 program consisted of the current, the initial resistance, the repetition frequency, the pulse width, and the thermal parameters; γ, α, and C_p. Using these data and equation (2), the program computed the temperature of the bridgewire at the end of the heating portion of the cycle. Having obtained this result equation (4) was used to find the temperature at the end of the cooling portion of the cycle. The resistance of the bridgewire which corresponded to these temperatures was also calculated. The program also computed the energy absorbed in the heating portion of each cycle. The computation was then repeated using the temperature and resistance at the end of the cooling portion of the cycle as the values for the start of the next cycle. After each cycle tests were made of the maximum temperature of the cycle, the increase in this temperature over that of the preceding cycle, and the number of cycles computed. These values were compared with preassigned values of these quantities. Computation ceased after the preassigned number of cycles or if the temperature exceeded the preassigned value for the maximum temperature, which usually was 2,000°C, or if the increase in temperature over the preceding cycle was less than one half of one percent. Otherwise, computation proceeded to the next cycle.

3.2 The initial resistance in almost all cases was taken to be 1.0 ohm. Pulse repetition frequencies from 60 to 3,000 cycles per second were studied. In most cases the on time for the pulse was short compared with the total time of the cycle and small compared to the thermal time constant τ. Under these conditions the cooling portion of the cycle can be considered to be independent of the pulse width. The temperature rise during a pulse will be a function of the energy. Thus, for any given pulse frequency the same maximum peak temperature will be reached for any combination of current, resistance, and pulse width for which the product I^2RW is constant.

3.3 Results printed out (Figure 4) included the resistance and temperature at the beginning and end of the heating portion of the cycle, the energy of the heating portion of the cycle, and the total energy used in this and previous cycles. Computations were carried out for different combinations of current, pulse repetition frequency, and pulse width selected so as to give maximum peak temperatures of 2,000°C or less.

3.4 It was found that if the logarithm of I is plotted against the logarithm of the pulse width for any given frequency and maximum temperature, the result is very nearly a straight line. This was done for several representative frequencies and is shown in Figures 5 and 6. In each case lines were drawn representing temperatures of 300, 500, and 1,000°C. The results of the calculations can all be combined into a single graph in which the product I^2RW is the ordinate and the pulse repetition frequency is the abscissa. The results can be shown by drawing contour lines representing the attained maximum peak temperature (Figure 7). In order to locate these contour lines it was convenient to use a method of computation which would have a given temperature as part of the input data and calculate the point corresponding to this temperature for some given combination of the other variables.

3.5 Appendix B gives the program as it was modified to accomplish this result. The modified program was arranged to find the pulse width which would give the desired maximum peak temperature for a given pulse repetition frequency. This is done by repeated interpolations between previously determined pairs of values of the pulse width and temperature. The program begins with two pulse widths and their corresponding maximum temperatures. It then interpolates or extrapolates for the pulse width corresponding to the desired temperature. Using this value of the pulse width it then computes the maximum peak temperature as in the previous program. This temperature is compared with the desired temperature. If the difference is less than 5°C, the computation ceases. Otherwise, the new pulse width and temperature replace one of the previous pairs of values and the process is repeated. One of the original pairs of pulse width and temperature values can be taken to be zeros; the other pair may be merely an estimate for which no great accuracy is required. The process will find a satisfactory value for the pulse width within a few iterations.

3.6 Values of $I^2R°W$ for frequencies of pulse repetition frequency from twenty to two thousand cycles per second giving maximum peak temperatures of 300, 500, and 1,000°C above ambient temperature were computed in this way and are given in Table 1. These results are also shown graphically with contour lines for the maximum temperatures drawn. In order to simplify the location of the ordinate value for this graph, a simple nomogram was designed which gives the ordinate for known values of I and W with resistance R. The nomogram is shown in Figure 8. These computations used typical values of the thermal parameters: γ, 600 microwatts per degree; α, 705 parts per million per degree* and C_p, 2.4 microjoules per degree. A few calculations were made using a value for α of 900 parts per million per degree. Temperature reached under these conditions are higher

*It should be noted that α is a temperature dependent constant and must be selected to correspond to the base temperature from which resistance calculations are made. If the base temperature or base resistance changes then α must also be changed.

than for the smaller value of α. The difference is greater when comparing the maximum peak temperature than when comparing the first pulses. For the first pulse the difference is of the order of 5%. At higher frequencies the maximum peak temperatures differ by about 15%. Utilization of the computational technique therefore requires a realistic choice of numerical values for the various parameters. Experience to date has shown that the determination of $\bar{R}$ is less subject to experimental error and is less variable than that of the other parameters. The determination of γ and C_p is the least precise since the error of their determination must include the error of determination of α. The extremes of the individual values of the most variable parameter rarely exceed 0.6 to 1.5 times the central value.

4. CONCLUSIONS

4.1 The results obtained in this investigation have been summarized in Table 1 and as a nomograph (Figure 8). The table gives initial conditions which determine the pulse size required to heat one particular type of bridgewire ultimately to a maximum peak temperature of 300, 500, or 1,000°C above ambient for pulse repetition frequencies from 20 to 2,000 cycles per second. The initial conditions are most conveniently expressed as a pseudo-energy per burst term in units of microjoules per burst. This term is computed on the assumption that the pulse power is maintained at its initial value (the power level before any bridgewire resistance change occurs). The actual pulse energy will, of course, be greater than this due to the heating and corresponding resistance increase of the bridgewire.

4.2 The computed results can be used to assess the expected response of an EED to a particular electromagnetic energization. If values of $\bar{R}$, α, γ, and C_p are known for a particular EED, it is possible to compute the interrelationships between: (a) maximum peak temperature, (b) pulse repetition frequency, and (c) initial pulse magnitude (which in turn can be broken down to pulse width and initial pulse amplitude). For instance, for the Squib, Mk 1 Mod 0, a temperature rise of 500°C would be expected at a pulse repetition frequency of 2,000 cycles per second for a 10-ampere pulse with a pulse width of 1.1 microsecond. The same temperature would be attained at pulse repetition frequencies below approximately 30 cycles per second for the same current amplitude provided the pulse width were 10.5 microseconds.

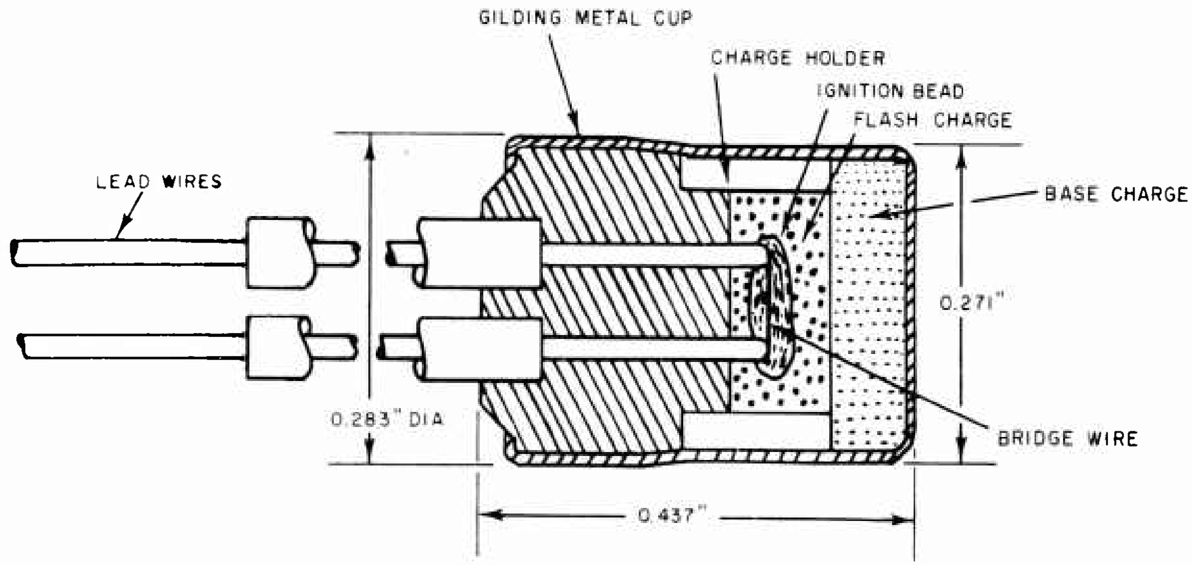
4.3 Once the temperature can be deduced the probability of initiation of the EED can in turn be estimated provided information is available as to the temperature which will cause initiation of the EED. This information usually can be found experimentally from DC pulse firing data. Inference of the necessary temperature based on the "Hot-Spot" Theory of Bowden and Yoffee (reference (a)) has been found to give satisfactory results (reference (3)).

4.4 Subsequent to the work herein reported a technique was devised to monitor the bridgewire heating and cooling of EEDs being energized by microwave energy from a 9-KMC radar. Qualitative and preliminary quantitative comparison show agreement between results and predicted values indicating that the phenomena of thermal stacking and the appearance of the time-temperature wave-forms as they are described herein are in accord with experiment.

Table 1

Relationship Between $I^2R\mathring{w}$ (microjoules), Pulse Repetition Frequency, and Equilibrium Peak Temperature

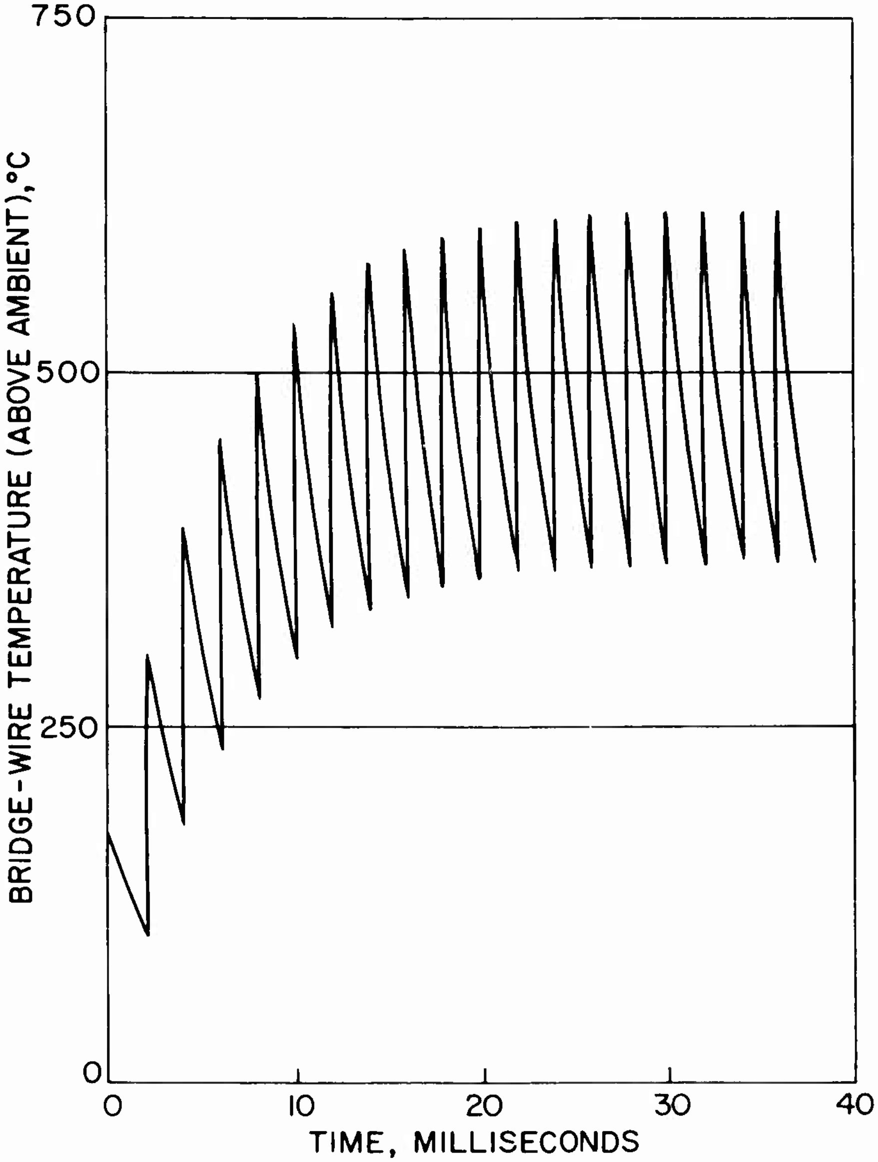
PULSE REPETITION FREQUENCY (cps)	EQUILIBRIUM PEAK TEMPERATURE (°C)		
	300	500	1000
20	653.1	1029.2	1819.9
40	652.3	1026.7	1814.7
60	642.3	1009.8	1778.3
100	594.5	928.4	1608.4
140	530.9	827.7	1408.1
200	452.6	695.1	1156.0
250	398.3	606.8	1019.3
300	353.9	539.4	878.5
600	211.5	315.7	505.0
1000	137.7	205.2	324.3
1400	103.0	152.6	240.1
2000	74.6	110.9	172.4



NOTES:

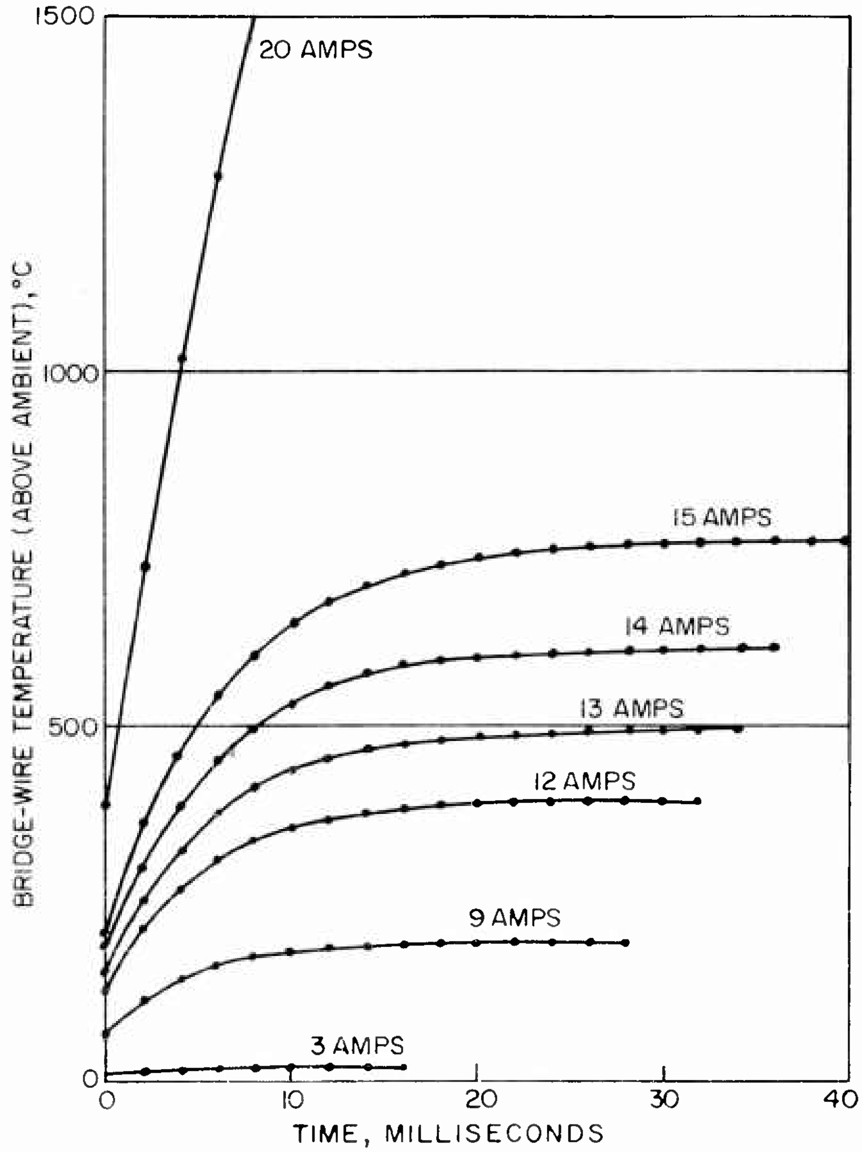
1. IGNITION BEAD - APPROX. 5 MG DDNP/$KClO_3$
2. FLASH CHARGE - APPROX. 45 MG BLACK POWDER
3. BASE CHARGE - APPROX. 45 MG BLACK POWDER
4. BRIDGE WIRE - 0.001" PLATINUM-IRIDIUM 0.060" LONG

FIG. 1 SQUIB MK 1 MOD 0



NOTE: CONSTANT CURRENT 14 AMP,
PULSE REPETITION FREQUENCY 499.5 CPS
PULSE WIDTH 2 MICROSECONDS

FIG. 2 THERMAL STACKING OF THE SQUIB, MK I BRIDGE



NOTE: CONSTANT CURRENT PULSES APPLIED TO SQUIB, MK I LOADED. PULSE REPETITION FREQUENCY 499.5 CPS PULSE WIDTH, 2 MICROSECONDS.

FIG. 3 THERMAL STACKING AS A FUNCTION OF PULSE AMPLITUDE

```
                                                                  THERMAL PARAMETERS
CURRENT     RESISTANCE    PULSES     PULSE WIDTH      GAMMA       ALPHA     CEE PEE
  AMPS         OHMS       PER SEC    MICROSECONDS   MICWTS/DEG  P/M/DEG   MICJLS/DEG
 10.00        1.000       200.00         4.568        600.0       705.0      2.400

         CYCLE COUNT          1                  ENERGY IN PULSE      0.489 MILLIJOULES
         ELAPSED TIME         5.00 MILLISEC      TOTAL ENERGY         0.489 MILLIJOULES
         TEMPERATURE                             RESISTANCE
           BEFORE PULSE       0.    DEG C          BEFORE PULSE       1.000 OHMS
           AFTER PULSE      203.59  DEG C          AFTER PULSE        1.144 OHMS

         CYCLE COUNT          2                  ENERGY IN PULSE      0.509 MILLIJOULES
         ELAPSED TIME        10.00 MILLISEC      TOTAL ENERGY         0.998 MILLIJOULES
         TEMPERATURE                             RESISTANCE
           BEFORE PULSE      58.40  DEG C          BEFORE PULSE       1.041 OHMS
           AFTER PULSE      270.97  DEG C          AFTER PULSE        1.191 OHMS

         CYCLE COUNT          3                  ENERGY IN PULSE      0.516 MILLIJOULES
         ELAPSED TIME        15.00 MILLISEC      TOTAL ENERGY         1.514 MILLIJOULES
         TEMPERATURE                             RESISTANCE
           BEFORE PULSE      77.72  DEG C          BEFORE PULSE       1.055 OHMS
           AFTER PULSE      293.28  DEG C          AFTER PULSE        1.207 OHMS

         CYCLE COUNT          4                  ENERGY IN PULSE      0.518 MILLIJOULES
         ELAPSED TIME        20.00 MILLISEC      TOTAL ENERGY         2.032 MILLIJOULES
         TEMPERATURE                             RESISTANCE
           BEFORE PULSE      84.12  DEG C          BEFORE PULSE       1.059 OHMS
           AFTER PULSE      300.67  DEG C          AFTER PULSE        1.212 OHMS

         CYCLE COUNT          5                  ENERGY IN PULSE      0.519 MILLIJOULES
         ELAPSED TIME        25.00 MILLISEC      TOTAL ENERGY         2.550 MILLIJOULES
         TEMPERATURE                             RESISTANCE
           BEFORE PULSE      86.24  DEG C          BEFORE PULSE       1.061 OHMS
           AFTER PULSE      303.12  DEG C          AFTER PULSE        1.214 OHMS

END OF FILE

END OF FILE
```

FIG. 4 TYPICAL PROGRAM PRINTOUT OF RESULTS

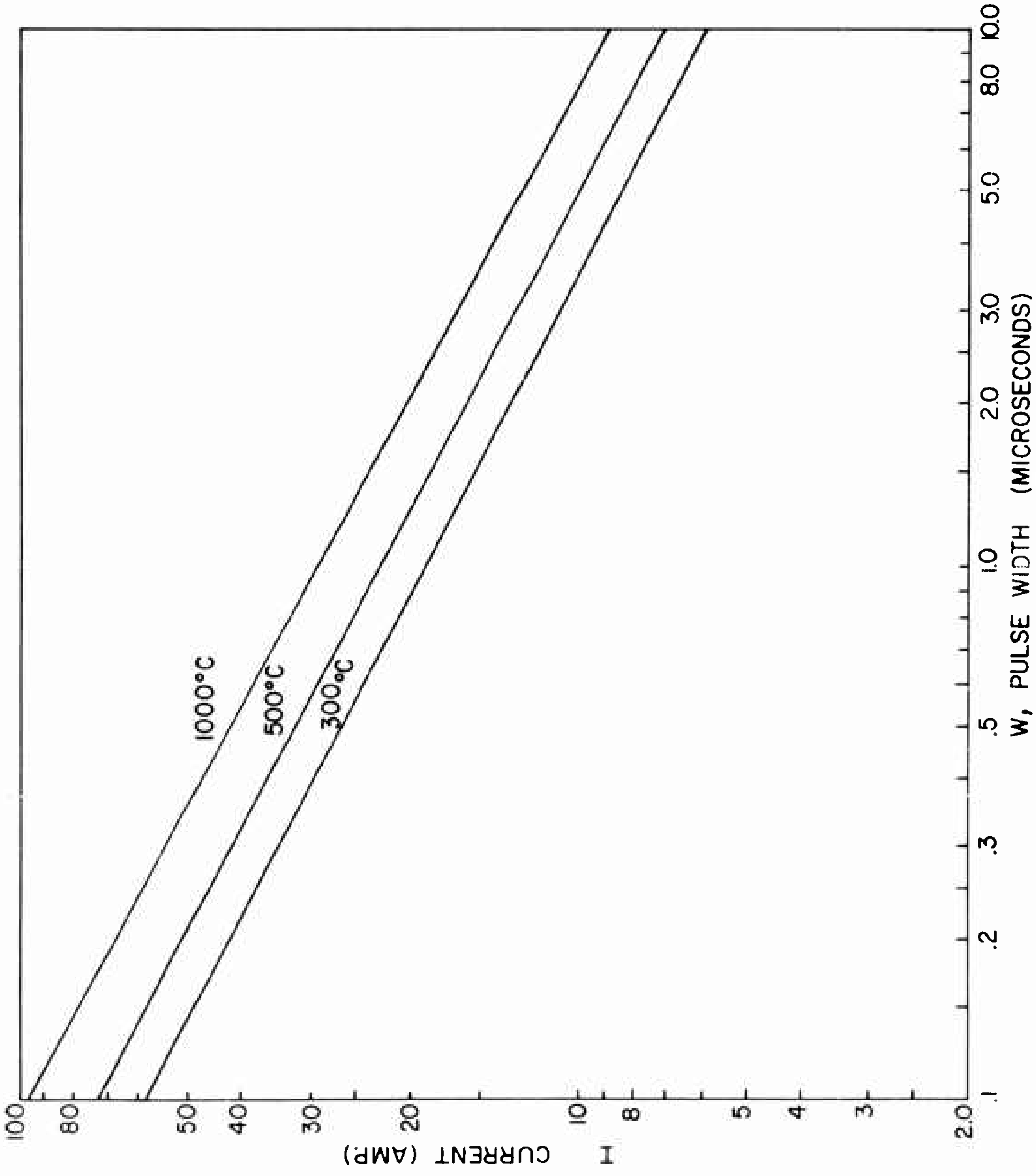


FIG.5 MAXIMUM PEAK TEMPERATURES FOR PULSE REPETITION
FREQUENCY OF 300 CPS

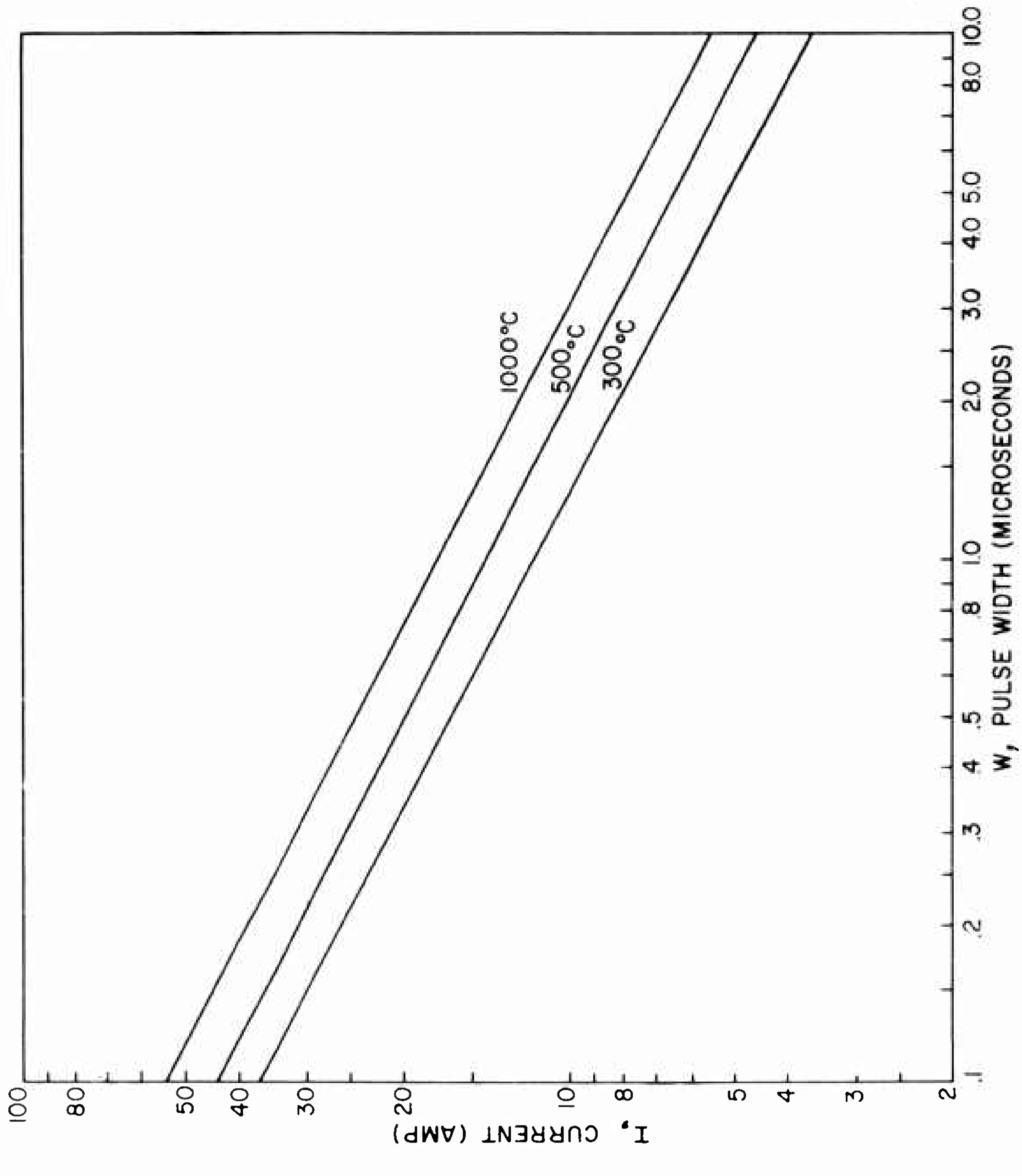


FIG.6 MAXIMUM PEAK TEMPERATURES FOR PULSE REPETITION FREQUENCY OF 1000CPS

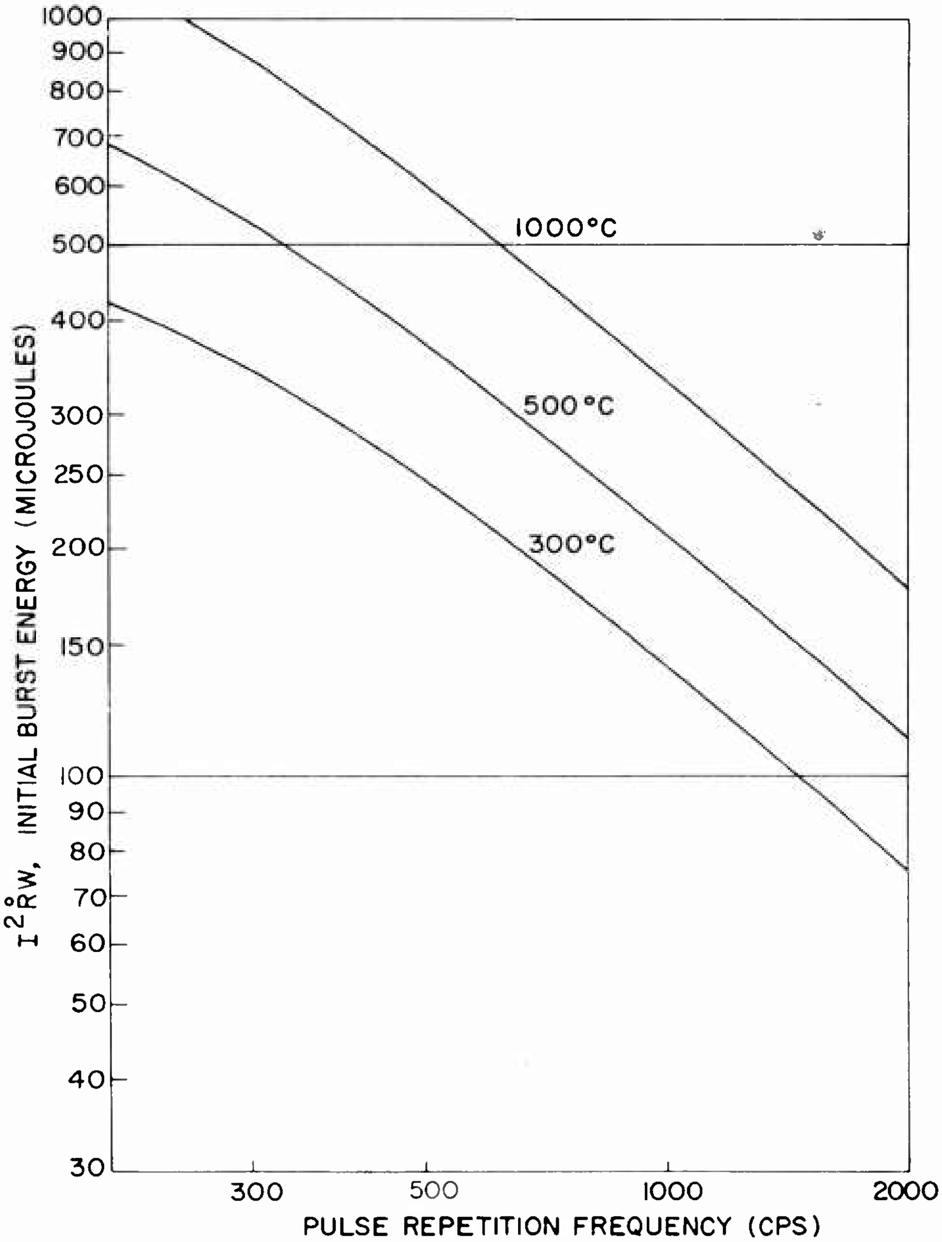
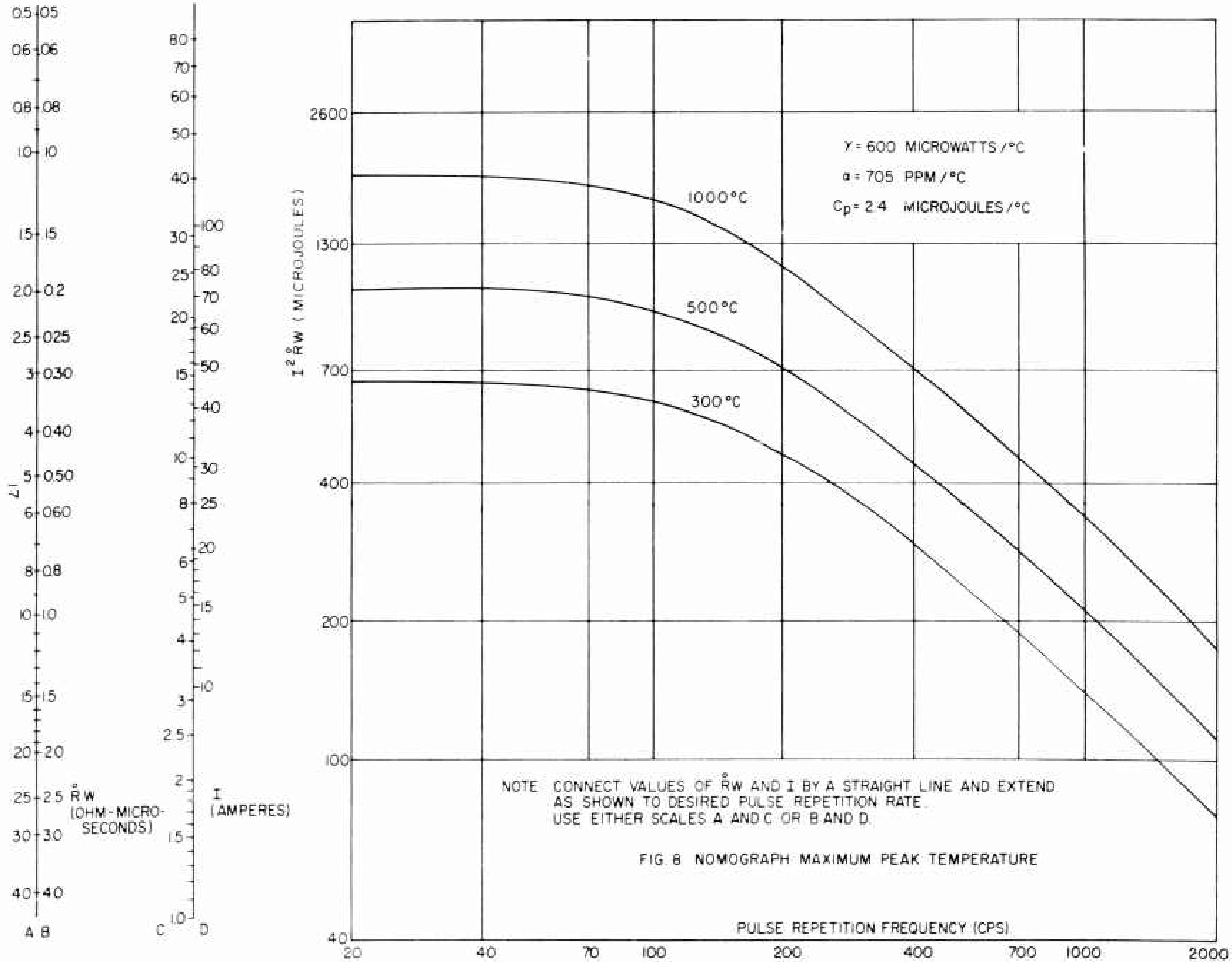


FIG. 7 MAXIMUM PEAK TEMPERATURES AS A FUNCTION OF PULSE PARAMETERS



NOTE CONNECT VALUES OF R̊W AND I BY A STRAIGHT LINE AND EXTEND AS SHOWN TO DESIRED PULSE REPETITION RATE. USE EITHER SCALES A AND C OR B AND D.

FIG. 8 NOMOGRAPH MAXIMUM PEAK TEMPERATURE

APPENDIX A

A-1. Fortran II is an Automatic Programming System of Formula Translation. It is a method of rewriting mathematical relations in a symbolic form which can be converted by a high speed digital computer into a productive sequential computational procedure. Fortran II can now be interpreted by a number of different makes of high speed computers.

A-2. Pages A-3 and A-4 are a photographically reproduced copy of the Fortran II listing of the computational program described in Paragraph 3.1. An exact keypunch duplication of this listing, one card per line, indluding all spaces within each line, should produce a source deck which can be compiled by any activity to whom Fortran II is available.

A-3. A description follows of each of the program symbols of quantities required for the computations.

Program Symbols:	TMAX	Upper bound of computed temperature of EED bridgewire in degrees Centigrade.
	PC	Ratio of maximum temperature attained in one pulse to that of preceding pulse which is considered to represent a stable temperature condition.
	NMAX	Maximum number of pulses to be computed.
	CUR	Constant current in amperes.
	RZ	Initial resistance in ohms.
	RATE	Pulse repetition frequency in cycles per second.
	TP	Time in seconds during which the constant current flows in each pulse.
	GAM	Heat loss factor, Gamma, in watts per degree Centigrade.
	ALF	Temperature coefficient of resistivity, Alpha, in ohms per ohm per degree Centigrade.
	CP	Heat capacity in joules per degree Centigrade.

APPENDIX A (cont'd)

Program Symbols:

T1	Temperature at the beginning of pulse.
R1	Resistance at the beginning of pulse.
T2	Temperature at end of heating portion of cycle.
R2	Resistance at end of heating portion of cycle.
T3	Temperature at end of cooling portion of cycle.
R3	Resistance at end of cooling portion of cycle.
TLST	Maximum temperature of preceding pulse.
TS	Length of cooling portion of cycle.
PENG	Energy in the pulse.
ENG	Total Energy.
TIME	Total time elapsed.

```
C       PROGRAM FOR FINDING TEMPERATURE-TIME HISTORY OF AN EED SUBJECTED
C       TO CONSTANT CURRENT RADAR-LIKE PULSES

    5 READ INPUT TAPE 0,301, TMAX,PC,NMAX
    7 NN=0
   10 READ INPUT TAPE 0,302,CUR,RZ,RATE,TP,GAM,ALF,CP
   11 IF(RATE) 115,115,12
   12 IF(1.0-TP*RATE) 115,115,16
   16 T1=0.0
   17 R1=RZ
   19 TLST=T1
   20 N=0
   21 ENG=0.0
   23 TS=1.0/RATE-TP
   24 EXP=0.36787944**(TS*GAM/CP)
   28 WRITE OUTPUT TAPE 0,304, CUR,RZ,RATE,TP,GAM,ALF,CP
   29 NN=NN+5
   30 CSQ=CUR**2
   31 ENZ=RZ*CSQ
   40 EN=R1*CSQ
   41 D=EN*ALF-GAM
   42 C=CP/D
   43 E=2.71828183**(TP/C)
   44 A=EN/D
   45 N=N+1
   46 B=A*ALF
   48 ED=E-1.0
   50 T2=T1+ED*A
   51 T3=T2*EXP
   52 R2=RZ*(1.0+ALF*T2)
   53 R3=RZ*(1.0+ALF*T3)
   60 PENG=EN*TP+B*(C*ED-TP)*ENZ
   62 ENG=ENG+PENG
   74 AN=N
   75 TIME=AN/RATE
   76 IF(NN-40) 79,79,77
   77 WRITE OUTPUT TAPE 0,307, N,PENG
      NN=0
   78 GO TO 80
   79 WRITE OUTPUT TAPE 0,308, N,PENG
   80 WRITE OUTPUT TAPE 0,309,TIME,ENG
   81 WRITE OUTPUT TAPE 0,310
   82 WRITE OUTPUT TAPE 0,311,T1,R1
   83 WRITE OUTPUT TAPE 0,312,T2,R2
   84 PX=(T2+273.0)/(TLST+273.0)
   86 IF(TMAX-T2) 7,7,87
   87 IF(PC-PX) 88,7,7
   88 IF(NMAX-N) 7,7,90
   90 R1=R3
   91 TLST=T2
   92 T1=T3
   93 NN=NN+6
   95 GO TO 40
  115 CALL RETURN
  116 STOP
  301 FORMAT(F9.0,F9.4,I9)
  302 FORMAT(3F8.0,4E11.4)
  304 FORMAT(1H164(1H )18HTHERMAL PARAMETERS/10(1H )78HCURRENT     RESIST
     1ANCE    PULSES     PULSE WIDTH      GAMMA        ALPHA       CEE PEE/12(1    304
     2H )78HAMPS          OHMS        PER SEC    MICROSECONDS   MICWTS/DEG   P/ 304
```

```
   3M/DEG    MICJLS/DEG/F16.2,F13.3,F11.2,6PF14.3,2F11.1,F12.3)
307 FCRMAT(1H116(1H  )11HCYCLE COUNTI1C,13(1H  )15HENERGY IN PULSE3PF11.
   13,12H MILLIJCULES)
308 FCRMAT(1H016(1H  )11HCYCLE COUNTI1C,13(1H  )15HENERGY IN PULSE3PF11.
   13,12H MILLIJCULES)
3C9 FCRMAT(17(1H  )12HELAPSEC TIME3PF12.2,25H MILLISEC TOTAL ENERGY
   1F11.3,12H MILLIJCULES)
31C FCRMAT(17(1H  )11HTEMPERATURE23(1H  )10HRESISTANCE)
311 FCRMAT(19(1H  )12HBEFORE PULSEF1C.2,24H DEG C       BEFORE PULSE
   1F12.3,5H OHMS)
312 FCRMAT(19(1H  )11HAFTER PULSEF11.2,23H DEG C       AFTER PULSE
   1F13.3,5H OHMS)
```

APPENDIX B

B-1. Appendix B contains the Fortran II listing for the computational program described in Paragraph 3.5 together with a listing of symbols used in this program which were not used in the first program. The list of symbols given in Appendix A applies to this program as well as that in Appendix A. The computational program consists of a main program and a subroutine. A photographically reproduced copy of the listing for these programs is given following the list of symbols.

Program Symbols:	TBS	Maximum peak temperature in degrees Centigrade.
	TP1	First pulse width in seconds.
	TEMP1	Maximum peak temperature in degrees Centigrade which corresponds to a pulse width of TP1.
	TP2	Second pulse width in seconds.
	TEMP2	Maximum peak temperature in degrees Centigrade which corresponds to a pulse width of TP2.

TP1 and TEM1 may both be zeros. If it is known that one pair of estimates is better than the other this pair should be selected as TP2 and TEM2.

```
C       MAIN PROGRAM FOR FINDING PULSE LENGTH WHICH WOULD GIVE A STATED
C       FINAL TEMPERATURE    USES SUBROUTINE TEMP(TP,T2)

        COMMON TMAX,PC,NMAX,GAM,ALF,CP,CUR,RZ,RATE
      5 READ INPUT TAPE 0,101, TMAX,PC,NMAX,GAM,ALF,CP
     10 READ INPUT TAPE 0,102,CUR,RZ,RATE,TBS,TP2,TEM2,TP1,TEM1
     11 IF(RATE) 40,40,12
     12 N=0
     25 TP=TP2+(TBS-TEM2)*(TP2-TP1)/(TEM2-TEM1)
     30 TP1=TP2
     31 TEM1=TEM2
     32 TP2=TP
     33 N=N+1
     34 CALL TEMP(TP2,TEM2)
     35 IF(N-5) 38,38,10
     38 IF(ABSF(TEM2-TBS)-5.0) 10,10,25
     40 CALL RETURN
     45 STOP
    101 FORMAT(F8.0,F8.4,I8,3E11.4)
    102 FORMAT (4F8.0,2(E11.4,F8.2))


C       SUBROUTINE FOR USE WITH PRECEDING PROGRAM

        SUBROUTINE TEMP(TP,T2)
        COMMON TMAX,PC,NMAX,GAM,ALF,CP,CUR,RZ,RATE
      7 NN=0
     12 IF(1.0-TP*RATE) 115,115,16
     16 T1=0.0
     17 R1=RZ
     19 TLST=T1
     20 N=0
     21 ENG=0.0
     23 TS=1.0/RATE-TP
     24 EXP=0.36787944**(TS*GAM/CP)
     28 WRITE OUTPUT TAPE 0,304, CUR,RZ,RATE,TP,GAM,ALF,CP
     29 NN=NN+5
     30 CSQ=CUR**2
     31 ENZ=RZ*CSQ
     40 EN=R1*CSQ
     41 D=EN*ALF-GAM
     42 C=CP/D
     43 E=2.71828183**(TP/C)
     44 A=EN/D
     45 N=N+1
     46 B=A*ALF
     48 ED=E-1.0
     50 T2=T1+ED*A
     51 T3=T2*EXP
     52 R2=RZ*(1.0+ALF*T2)
     53 R3=RZ*(1.0+ALF*T3)
     60 PENG=EN*TP+B*(C*ED-TP)*ENZ
     62 ENG=ENG+PENG
     74 AN=N
     75 TIME=AN/RATE
     76 IF(NN-40) 79,79,77
     77 WRITE OUTPUT TAPE 0,307, N,PENG
```

```
    NN=0
 78 GC TO 80
 79 WRITE CUTPUT TAPE 0,308, N,PENG
 80 WRITE CUTPUT TAPE 0,309,TIME,ENG
 81 WRITE CUTPUT TAPE 0,310
 82 WRITE CUTPUT TAPE 0,311,T1,R1
 83 WRITE CUTPUT TAPE 0,312,T2,R2
 84 PX=(T2+273.0)/(TLST+273.0)
 86 IF(TMAX-T2) 89,89,87
 87 IF(PC-PX) 88,89,89
 88 IF(NMAX-N) 89,89,90
 89 RETURN
 90 R1=R3
 91 TLST=T2
 92 T1=T3
 93 NN=NN+6
 95 GC TO 40
115 CALL RETURN
116 STCP
304 FCRMAT(1H164(1H )18HTHERMAL PARAMETERS/10(1H )78HCURRENT    RESIST
   1ANCE    PULSES    PULSE WIDTH     GAMMA       ALPHA      CEE PEE/12(1
   2H )78HAMPS         OHMS       PER SEC    MICROSECONDS  MICWTS/DEG   P/
   3M/DEG    MICJLS/DEG/F16.2,F13.3,F11.2,6PF14.3,2F11.1,F12.3)
307 FCRMAT(1H116(1H )11HCYCLE COUNTI10,13(1H )15HENERGY IN PULSE3PF11.
   13,12H MILLIJCULES)
308 FCRMAT(1H016(1H )11HCYCLE COUNTI10,13(1H )15HENERGY IN PULSE3PF11.
   13,12H MILLIJCULES)
309 FCRMAT(17(1H )12HELAPSED TIME3PF12.2,25H MILLISEC TOTAL ENERGY
   1F11.3,12H MILLIJCULES)
310 FCRMAT(17(1H )11HTEMPERATURE23(1H )10HRESISTANCE)
311 FCRMAT(19(1H )12HBEFORE PULSEF10.2,24H DEG C        BEFORE PULSE
   1F12.3,5H OHMS)
312 FCRMAT(19(1H )11HAFTER PULSEF11.2,23H DEG C       AFTER PULSE
   1F13.3,5H OHMS)
```

DISTRIBUTION

	Copies
Director of Defense Research and Development Department of Defense Washington 25, D. C.	1
Chief of Naval Operations (OP 411H) Department of the Navy Washington 25, D. C.	1
Chief, Bureau of Naval Weapons Department of the Navy Washington 25, D. C.	
DIS-32	2
RRRE-8	1
RUME-3	1
RUME-32	1
RMMP-3	1
RMMO-4	1
RREN-312	1
Director Special Projects Office Washington 25, D. C.	
SP-20	4
SP-27	1
Chief, Bureau of Ships Department of the Navy Washington 25, D. C. Code 423	2
Chief, Bureau of Yards & Docks Department of the Navy Washington 25, D. C. Code D-200	1
Chief of Naval Research Department of the Navy Washington 25, D. C. Chemistry Branch	2
Commandant U. S. Marine Corps Washington 25, D. C.	1
Commander Operational Development Force U. S. Atlantic Fleet U. S. Naval Base Norfolk 11, Virginia	2

	Copies
Commander	
U. S. Naval Ordnance Test Station	
China Lake, California	1
Code 556	1
Code 4572	1
Technical Library	2
B. A. Breslow	1
J. Sherman	1
Director	
Naval Research Laboratory	
Washington 25, D. C.	
Technical Information Section	2
Director	
David Taylor Model Basin	
Washington 7, D. C.	
Dr. A. H. Keil	2
Commander	
Naval Air Development Center	
Johnsville, Pennsylvania	
Aviation Armament Laboratory	1
Commander	
U. S. Naval Weapons Laboratory	
Dahlgren, Virginia	
Technical Library	2
J. Payne (WH Div.)	1
L. Pruett	1
J. Gray	1
P. Altman	1
Commander	
U. S. Naval Air Test Center	
Patuxent River, Maryland	1
Commander	
Pacific Missile Range	
Point Mugu, California	1
Commanding Officer	
U. S. Naval Weapons Station	
Yorktown, Virginia	
R & D Division	2
Commanding Officer	
U. S. Naval Ordnance Laboratory	
Corona, California	2

	Copies
Commanding Officer U. S. Naval Propellant Plant Indian Head, Maryland	
Technical Library	1
EODTC	1
Commander Naval Radiological Defense Laboratory San Francisco, California	1
Commander U. S. Naval Weapons Plant Washington 25, D. C.	1
Commanding Officer U. S. Naval Ordnance Plant Macon, Georgia	1
Commanding Officer U. S. Naval Ammunition Depot McAlester, Oklahoma	
R. E. Halpern	1
Commanding Officer U. S. Naval Ammunition Depot Waipele Branch Oahu, Hawaii	
Special Projects Officer Quality Evaluation Laboratory	1
Commanding Officer U. S. Naval Ammunition Depot Navy Number Six Six (66) c/o Fleet Post Office San Francisco, California	1
Commanding Officer U. S. Naval Ammunition Depot Bangor, Maine	
Quality Evaluation Laboratory	1
Commanding Officer U. S. Naval Ammunition Depot Concord, California	
Quality Evaluation Laboratory	1
Commanding Officer U. S. Navy Electronics Laboratory San Diego 52, California	1

	Copies
Commanding Officer U. S. Naval Underwater Ordnance Station Newport, Rhode Island	1
Commanding Officer U. S. Naval Weapons Evaluation Facility Kirtland Air Force Base Albuquerque, New Mexico	1
Superintendent Naval Post Graduate School Monterey, California	1
Commanding Officer Naval Torpedo Station Keyport, Washington	1
Office of Chief of Ordnance Department of the Army Washington 25, D. C.	
ORDGU	1
ORDTN	1
ORDTB	1
Office of Chief of Engineers Department of the Army Washington 25, D. C.	
ENGNB	1
ENGEB	1
Office of Chief Signal Officer Research & Development Division Washington 25, D. C.	1
Commanding General Picatinny Arsenal Dover, New Jersey	
ORDBB-TH8	1
ORDBB-TJ1	1
ORDBB-TK3	1
ORDBB-TM1	1
ORDBB-TP1	1
ORDBB-TP2	1
ORDBB-TP3	1
ORDBB-TR2	1
ORDBB-TS1	1

	Copies
Commanding Officer Army Signal Research & Development Laboratory Fort Monmouth, New Jersey	1
Commanding Officer Office of Ordnance Research Duke Station Durham, North Carolina	1
Commander U. S. Army Ordnance Frankford Arsenal Philadelphia 37, Pennsylvania	1
Commander U. S. Army Rocket & Guided Missile Agency Redstone Arsenal, Alabama	1
Commanding Officer Diamond Ordnance Fuze Laboratory Connecticut Ave. & Van Ness St., N. W. Washington 25, D. C.	
Ordnance Development Laboratory	1
M. Lipnick (Code 005)	1
R. Comyn (Code 710)	1
G. Keehn (Code 320)	1
Chief of Staff U. S. Air Force Washington 25, D. C. AFORD-AR	1
Commander Wright Development Center Wright-Patterson Air Force Base Dayton, Ohio	1
Headquarters, Air Proving Ground Center U. S. Air Force, ARDC Eglin Air Force Base, Florida PGTRI, Technical Library	1
Commander Air Research & Development Command Andrews Air Force Base Washington 25. D. C.	1

	Copies
Commander Rome Air Development Center Griffis Air Force Base Rome, New York	1
Commander Holloman Air Development Center Alamagordo, New Mexico	1
Commanding Officer Air Force Missile Test Center Patrick Air Force Base, Florida	1
Commander Air Force Cambridge Research Center L. G. Hanscom Field Bedford, Massachusetts	1
Commander Hill Air Force Base Florida OOAMA	1
Armed Services Technical Information Agency Arlington Hall Station Arlington, Virginia TIPDR	10
Office of Technical Services Department of Commerce Washington 25, D. C.	100
Director U. S. Bureau of Mines Division of Explosive Technology 4800 Forbes Street Pittsburgh 13, Pennsylvania	1
Atomic Energy Commission Washington 25, D. C. DMA	1
Lawrence Radiation Laboratory University of California P. O. Box 808 Livermore, California Technical Information Division	1

	Copies
Director Los Alamos Scientific Laboratory P. O. Box 1663 Los Alamos, New Mexico Library	1
Stavid Engineering, Inc. U. S. Route 22 Plainfield, New Jersey	1
Vitro Corporation 14000 Georgia Avenue Silver Spring, Maryland	1
Western Cartridge Company Division of Olin Industries East Alton, Illinois	1
Denver Research Institute University of Denver Denver 10, Colorado	1
Universal Match Corporation Marion, Illinois Mr. Wm. Rose	1
Universal Match Corporation Marion, Illinois	1
Bermite Powder Company Saugus, California	1
Field Command, Defense Atomic Support Agency Albuquerque, New Mexico FCDR	1
Defense Atomic Support Agency Washington 25, D. C.	2
Commanding General U. S. Army Proving Ground Aberdeen, Maryland BRL	1
Commanding Officer Engineer Research & Development Laboratory U. S. Army, Fort Belvoir, Virginia	1

	Copies
Commanding General White Sands Proving Ground White Sands, New Mexico	1
Sandia Corporation P. O. Box 5400 Albuquerque, New Mexico	1
Sandia Corporation P. O. Box 969 Livermore, California	1
Lockheed Aircraft Corporation P. O. Box 504 Sunnyvale, California	1
Librascope-Sunnyvale 670 Arques Avenue Sunnyvale, California	1
Director, Applied Physics Laboratory Johns Hopkins University 8621 Georgia Avenue Silver Spring, Maryland	1
Solid Propellants Agency	1
Commanding Officer Fort Dietrick, Maryland	1
Commanding Officer Rock Island Arsenal Rock Island, Illinois	1
Commanding Officer Watertown Arsenal Watertown 72, Massachusetts	1
Commanding General Redstone Arsenal Huntsville, Alabama Technical Library	1
Commander, Ordnance Corps Lake City Arsenal Independence, Missouri Industrial Engineering Division	1

	Copies
Director, USAF Project RAND Via: USAF Liaison Office The RAND Corporation 1700 Main Street Santa Monica, California	1
Aerojet General Corporation Ordnance Division Downey, California Dr. L. Zernow	1
Stanford Research Institute Poulter Laboratories Menlo Park, California	1
Explosives Research Group University of Utah Salt Lake City, Utah	1
Beckman Instruments, Ind. 525 Mission Street South Pasadena, California	1
Bulova Research & Development, Inc. 52-10 Woodside Avenue Woodside 77, New York M. Enneman	1
E. I. duPont deNemours Eastern Laboratories Explosives Department Gibbstown, New Jersey	1
Alleghaney Ballistics Laboratory Cumberland, Maryland	1
The Franklin Institute 20th & Benjamin Franklin Parkway Philadelphia, Pennsylvania	1
Welex Electronics Corporation Solar Building, Suite 201 16th & K Streets, N. W. Washington 25, D. C.	1
American Machine & Foundry Co. 1025 North Royal Street Alexandria Virginia Dr. L. F. Dytrt	1

	Copies
Atlas Powder Company Reynolds Ordnance Section P. O. Box 271 Tamaqua, Pennsylvania Mr. R. McGirr	1
Grumman Aircraft Engineering Corporation Weapons Systems Department Bethpage, Long Island, New York Mr. R. M. Carbee	1
Jansky and Bailey, Inc. 1339 Wisconsin Avenue, N. W. Washington, D. C. Mr. F. T. Mitchell, Jr.	1
McCormick Selph Institute Hollister, California Technical Library	1
Midwest Research Institute 425 Volker Boulevard Kansas City, Missouri Security Officer	1
RCA Service Company Systems Engineering Facility (E. B. Johnston) Government Service Department 838 N. Henry Street Alexandria, Virginia	1
Redel, Incorporated 2300 E. Katella Avenue Anaheim, California Library	1
Armed Services Explosives Safety Board Department of Defense Room 2075, Bldg. T-7, Gravelly Point Washington 25, D. C.	1
U. S. Flare Division Atlantic Research Corporation 19701 W. Goodvale Road Saugus, California Mr. E. E. Elzufon, Head R&D Group	1

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 61-108)
CHARACTERIZATION OF SQUIB MK 1 MOD 0: THERMAL STACKING FROM RADAR-LIKE PULSES (U), by L.D. Hampton and J.N. Ayres. 15 Sept. 1961. v.p. charts. UNCLASSIFIED

The electro-thermal equations describing the heating and cooling of wire bridge electro-explosive devices are solved for constant-current radar-type input pulses. The bridgewire temperature-time history is obtained for a variety of pulse amplitudes and repetition frequencies. Equilibrium temperatures are obtained for the varied input conditions and are all combined in a single nomograph. If the hot-spot theory is assumed the conditions for explosion can be deduced.

1. Squibs - Mark 1 mod 0
2. Electro-explosive devices
3. Wire, Bridge - Temperatures

I. Title
II. Hampton, Laurence D.
III. Ayres, James N., jt. author

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 61-108)
CHARACTERIZATION OF SQUIB MK 1 MOD 0: THERMAL STACKING FROM RADAR-LIKE PULSES (U), by L.D. Hampton and J.N. Ayres. 15 Sept. 1961. v.p. charts. UNCLASSIFIED

The electro-thermal equations describing the heating and cooling of wire bridge electro-explosive devices are solved for constant-current radar-type input pulses. The bridgewire temperature-time history is obtained for a variety of pulse amplitudes and repetition frequencies. Equilibrium temperatures are obtained for the varied input conditions and are all combined in a single nomograph. If the hot-spot theory is assumed the conditions for explosion can be deduced.

1. Squibs - Mark 1 mod 0
2. Electro-explosive devices
3. Wire, Bridge - Temperatures

I. Title
II. Hampton, Laurence D.
III. Ayres, James N., jt. author

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 61-108)
CHARACTERIZATION OF SQUIB MK 1 MOD 0: THERMAL STACKING FROM RADAR-LIKE PULSES (U), by L.D. Hampton and J.N. Ayres. 15 Sept. 1961. v.p. charts. UNCLASSIFIED

The electro-thermal equations describing the heating and cooling of wire bridge electro-explosive devices are solved for constant-current radar-type input pulses. The bridgewire temperature-time history is obtained for a variety of pulse amplitudes and repetition frequencies. Equilibrium temperatures are obtained for the varied input conditions and are all combined in a single nomograph. If the hot-spot theory is assumed the conditions for explosion can be deduced.

1. Squibs - Mark 1 mod 0
2. Electro-explosive devices
3. Wire, Bridge - Temperatures

I. Title
II. Hampton, Laurence D.
III. Ayres, James N., jt. author

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 61-108)
CHARACTERIZATION OF SQUIB MK 1 MOD 0: THERMAL STACKING FROM RADAR-LIKE PULSES (U), by L.D. Hampton and J.N. Ayres. 15 Sept. 1961. v.p. charts. UNCLASSIFIED

The electro-thermal equations describing the heating and cooling of wire bridge electro-explosive devices are solved for constant-current radar-type input pulses. The bridgewire temperature-time history is obtained for a variety of pulse amplitudes and repetition frequencies. Equilibrium temperatures are obtained for the varied input conditions and are all combined in a single nomograph. If the hot-spot theory is assumed the conditions for explosion can be deduced.

1. Squibs - Mark 1 mod 0
2. Electro-explosive devices
3. Wire, Bridge - Temperatures

I. Title
II. Hampton, Laurence D.
III. Ayres, James N., jt. author

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 61-108)
CHARACTERIZATION OF SQUIB MK 1 MOD 0: THERMAL STACKING FROM RADAR-LIKE PULSES (U), by L.D. Hampton and J.N. Ayres. 15 Sept. 1961. v.p. charts. UNCLASSIFIED

The electro-thermal equations describing the heating and cooling of wire bridge electro-explosive devices are solved for constant-current radar-type input pulses. The bridgewire temperature-time history is obtained for a variety of pulse amplitudes and repetition frequencies. Equilibrium temperatures are obtained for the varied input conditions and are all combined in a single nomograph. If the hot-spot theory is assumed the conditions for explosion can be deduced.

1. Squibs - Mark 1 mod 0
2. Electro-explosive devices
3. Wire, Bridge - Temperatures

I. Title
II. Hampton, Laurence D.
III. Ayres, James N., jt. author

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 61-108)
CHARACTERIZATION OF SQUIB MK 1 MOD 0: THERMAL STACKING FROM RADAR-LIKE PULSES (U), by L.D. Hampton and J.N. Ayres. 15 Sept. 1961. v.p. charts. UNCLASSIFIED

The electro-thermal equations describing the heating and cooling of wire bridge electro-explosive devices are solved for constant-current radar-type input pulses. The bridgewire temperature-time history is obtained for a variety of pulse amplitudes and repetition frequencies. Equilibrium temperatures are obtained for the varied input conditions and are all combined in a single nomograph. If the hot-spot theory is assumed the conditions for explosion can be deduced.

1. Squibs - Mark 1 mod 0
2. Electro-explosive devices
3. Wire, Bridge - Temperatures

I. Title
II. Hampton, Laurence D.
III. Ayres, James N., jt. author

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 61-108)
CHARACTERIZATION OF SQUIB MK 1 MOD 0: THERMAL STACKING FROM RADAR-LIKE PULSES (U), by L.D. Hampton and J.N. Ayres. 15 Sept. 1961. v.p. charts. UNCLASSIFIED

The electro-thermal equations describing the heating and cooling of wire bridge electro-explosive devices are solved for constant-current radar-type input pulses. The bridgewire temperature-time history is obtained for a variety of pulse amplitudes and repetition frequencies. Equilibrium temperatures are obtained for the varied input conditions and are all combined in a single nomograph. If the hot-spot theory is assumed the conditions for explosion can be deduced.

1. Squibs - Mark 1 mod 0
2. Electro-explosive devices
3. Wire, Bridge - Temperatures

I. Title
II. Hampton, Laurence D.
III. Ayres, James N., jt. author

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 61-108)
CHARACTERIZATION OF SQUIB MK 1 MOD 0: THERMAL STACKING FROM RADAR-LIKE PULSES (U), by L.D. Hampton and J.N. Ayres. 15 Sept. 1961. v.p. charts. UNCLASSIFIED

The electro-thermal equations describing the heating and cooling of wire bridge electro-explosive devices are solved for constant-current radar-type input pulses. The bridgewire temperature-time history is obtained for a variety of pulse amplitudes and repetition frequencies. Equilibrium temperatures are obtained for the varied input conditions and are all combined in a single nomograph. If the hot-spot theory is assumed the conditions for explosion can be deduced.

1. Squibs - Mark 1 mod 0
2. Electro-explosive devices
3. Wire, Bridge - Temperatures

I. Title
II. Hampton, Laurence D.
III. Ayres, James N., jt. author